Advanced Accelerators and Colliders

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On behalf of the
Plasma and Advanced Structure Accelerators Interest Group

Snowmass Agora on Future Colliders: Advanced Colliders

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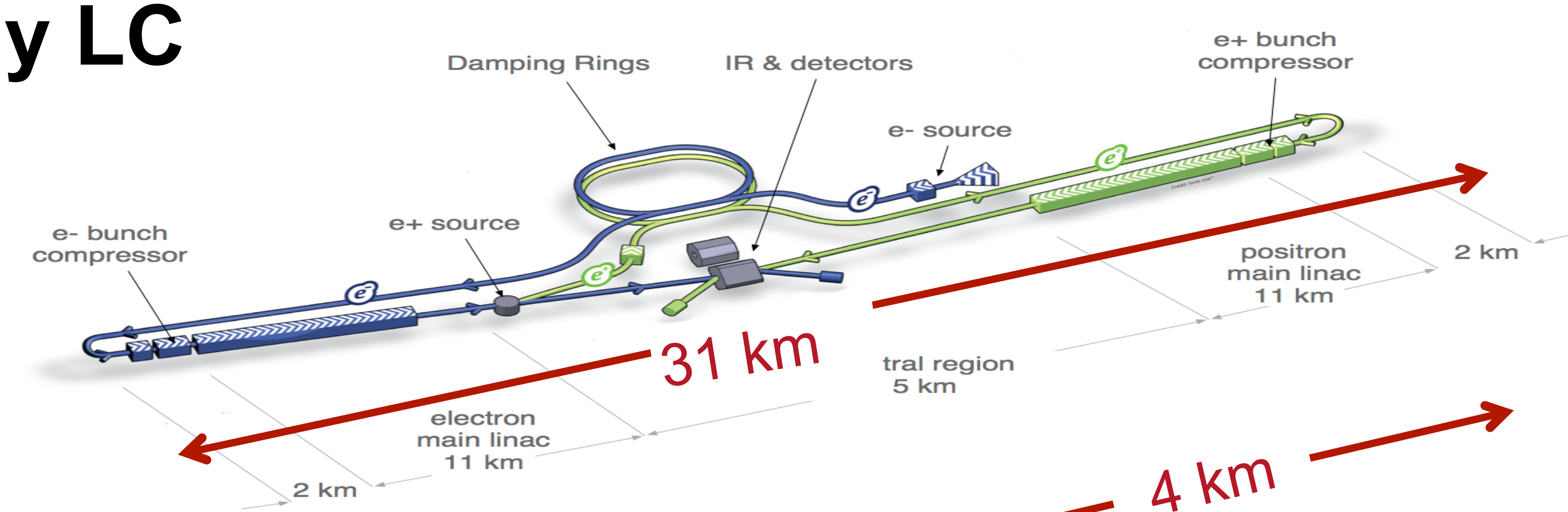
Office of Science

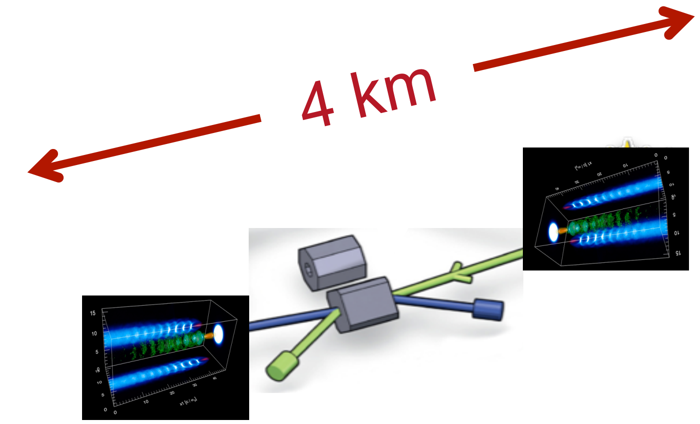
SLAC NATIONAL ACCELERATOR LABORATORY

The Scale for a TeV Linear Collider

Today's technology LC – a 31km tunnel:



Advanced Accelerator Technology LC:



- GeV/m accelerating gradient

The Luminosity Challenge:

$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)$$

- High-efficiency

…and must do it for positrons too!

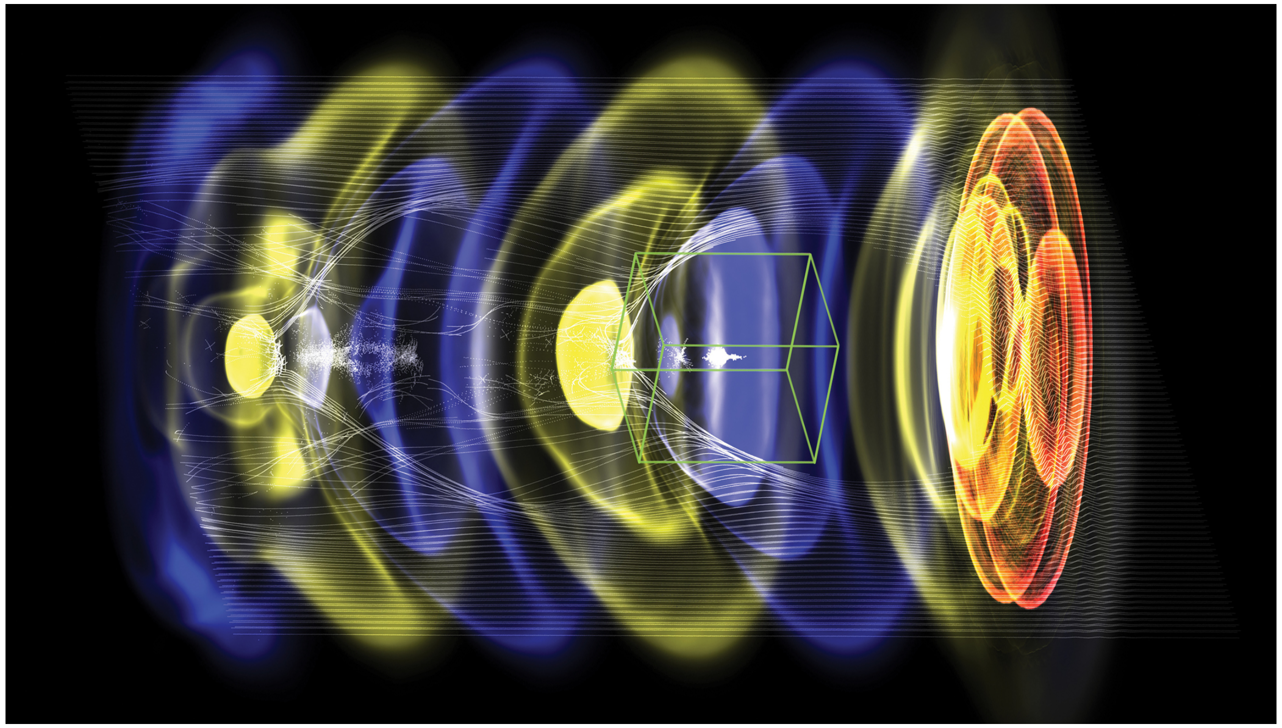
Advanced and Novel Accelerators (ANAs): Ultrahigh Fields Offer Potential from TeV to Many TeV

- Ultrahigh fields 1-100 GV/m
  - Smaller linacs, lower cost
- Ultrashort bunches 10 fs – 1 ps
  - Reduced beamstrahlung, lower drive power
- Rapid accelerator R&D progress in last decade
- Compact colliders: polarized e+e-, gamma-gamma

Structure-based wakefield accelerator (SWFA)

Plasma wakefield accelerator (PWFA)

Laser wakefield accelerator (LWFA)

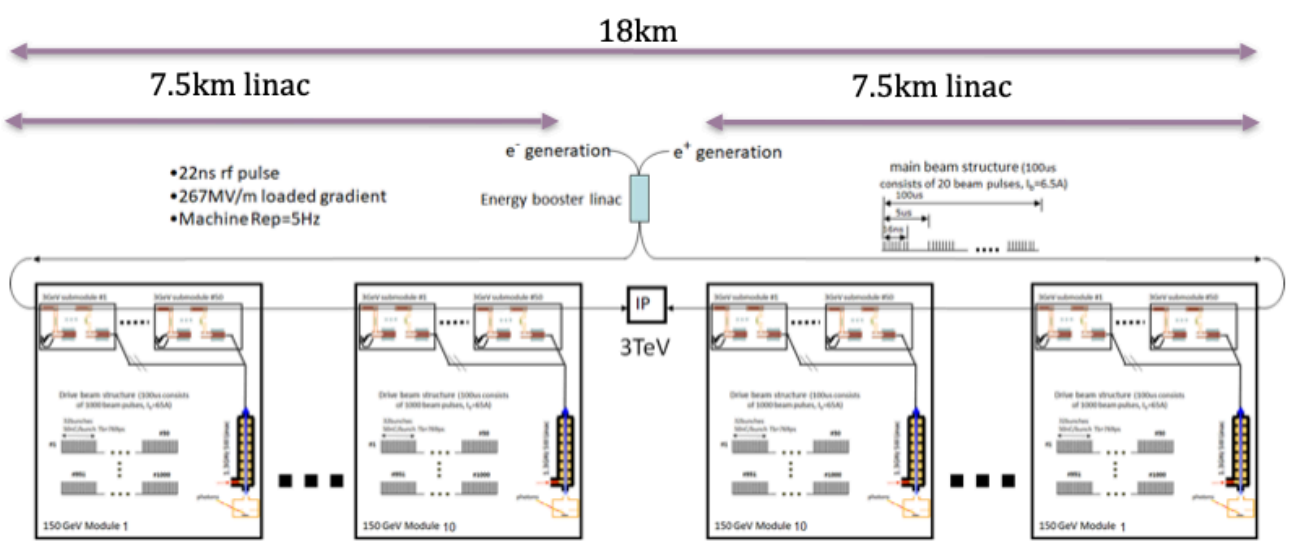


Example: a laser or particle beam (red) drives a density wave (blue to yellow) in plasma, accelerating electrons (white) with fields of order 10 GeV/m

Intense laser and particle beam driven plasmas or structures can circumvent current acceleration limits

Wakefield-based Colliders: Staged High-gradient Accelerators with Geometric Gradients 0.2 - 2 GeV/m

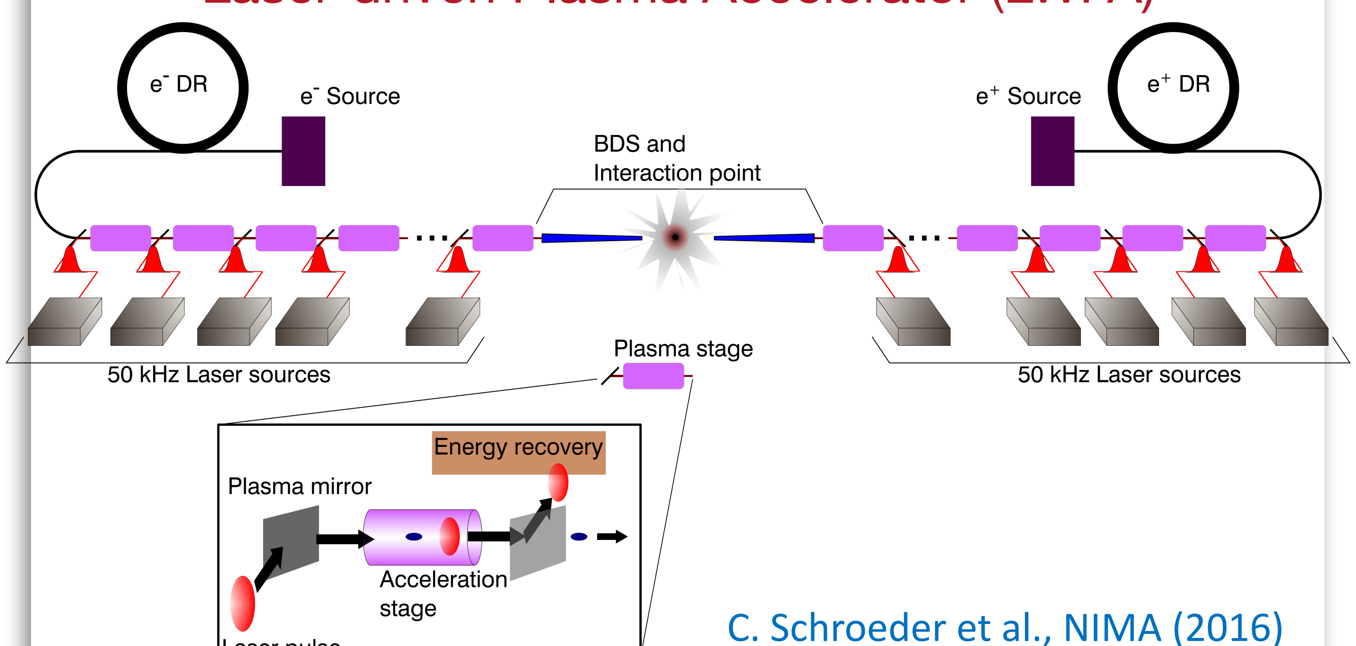
Structure Wakefield Accelerator (SWFA)



0.267 GeV/stage; Geometric gradient: 0.2 GV/m

https://accelconf.web.cern.ch/ipac2013/papers/tupea088.pdf

Laser-driven Plasma Accelerator (LWFA)

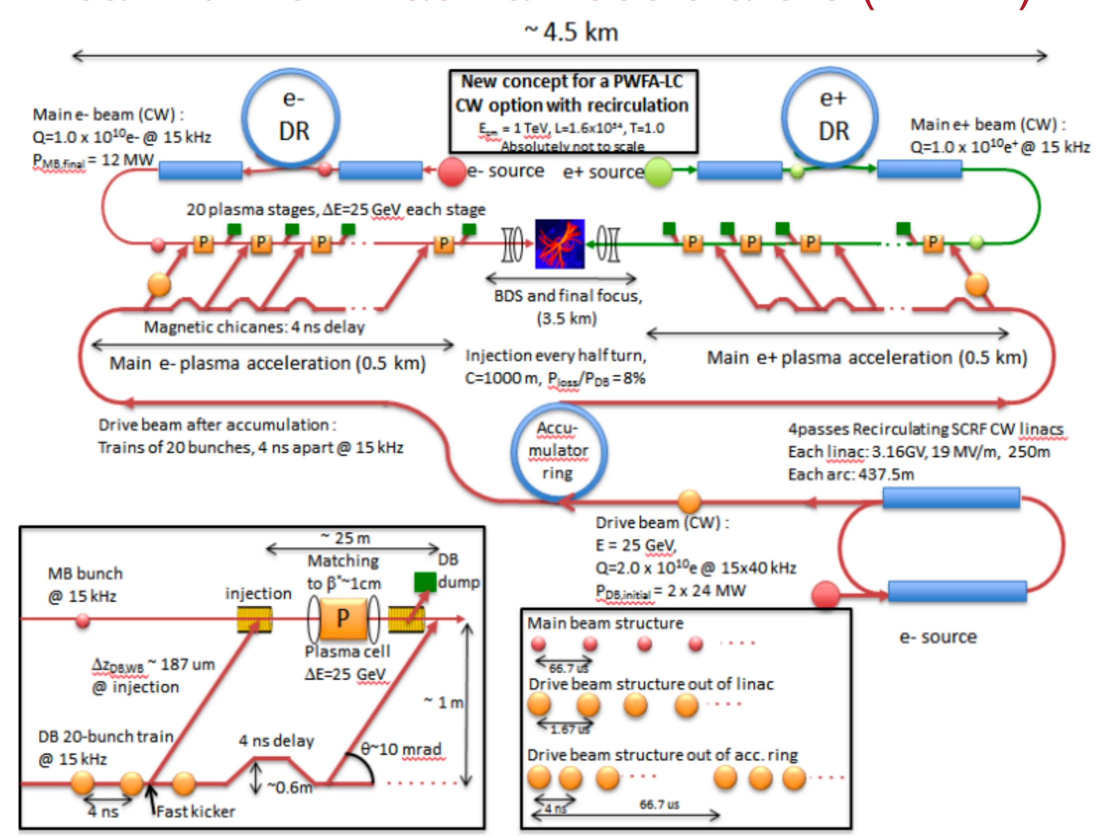


C. Schroeder et al., NIMA (2016)

5 GeV/stage; Geometric gradient: 2.3 GV/m

- Collider designs have been developed to guide research priorities (efficiency, staging…)
- Next step – integrated design studies

Beam-driven Plasma Accelerators (PWFA)



25 GeV/stage; Geometric gradient: 1 GV/m

E. Adli et al., arXiv:1308.1145 (2013); Chen et al., arXiv2009:13672

Collider Studies Establish Accessible Parameter Sets

Similar parameter ranges accessible to each technology: coordinated example

- TeV-class established previous Snowmass, now extended to 15 TeV
- Documented in Contributed Papers
- Potential to re-use infrastructure of near-term LC (e.g. ILC)
- Next steps for AF: integrated design study, self consistent and including tradeoffs

Sequence of collider options available – polarized e+e- or gamma-gamma

- New concepts continue to emerge that extend this potential

	Components				Performance Parameters				
Concept	**Accelerator Technology**	**Beam source**	**Interstage Coupling**	**Beam Delivery**	**Effective Gradient**	**Energy**	**Luminosity**	**Efficiency**	**Power (no recovery)**
ILC	SC RF	Damp. Ring	N/A	ILC BDS	31.5 MV/m	0.5 TeV	2.7E34		240 MW
AALC	Plasma or Str.	Damping	Trad. mag.	Trad. BDS	1 GeV/m	1 TeV	1E34	15%	70-100 MW
AALC	Plasma or Str.	Damping	Mag. or Plasma	Trad. BDS	1 or 10 GeV/m	3 TeV	3E34	15%	185-315 MW
AALC	Plasma or Str.	Plas. cath.@nm	Mag. or Plasma	Trad. BDS	1 or 10 GeV/m	3 TeV	1E35	15%	200-315 MW
AALC	Plasma or Str.	Plas. cath.@nm	Plas. lens	Trad. BDS	10 GeV/m	15 TeV	1E35	15%	900-1100 MW
AALC	Plasma or Str.	Plas. cath.@nm	Plas. lens	Plas. lens	10 GeV/m	15 TeV	5E35	15%	900-1100 MW

EF: Particle physics signature analysis needed to guide development, alternatives

Extending the Energy Reach of an Existing LC Facility

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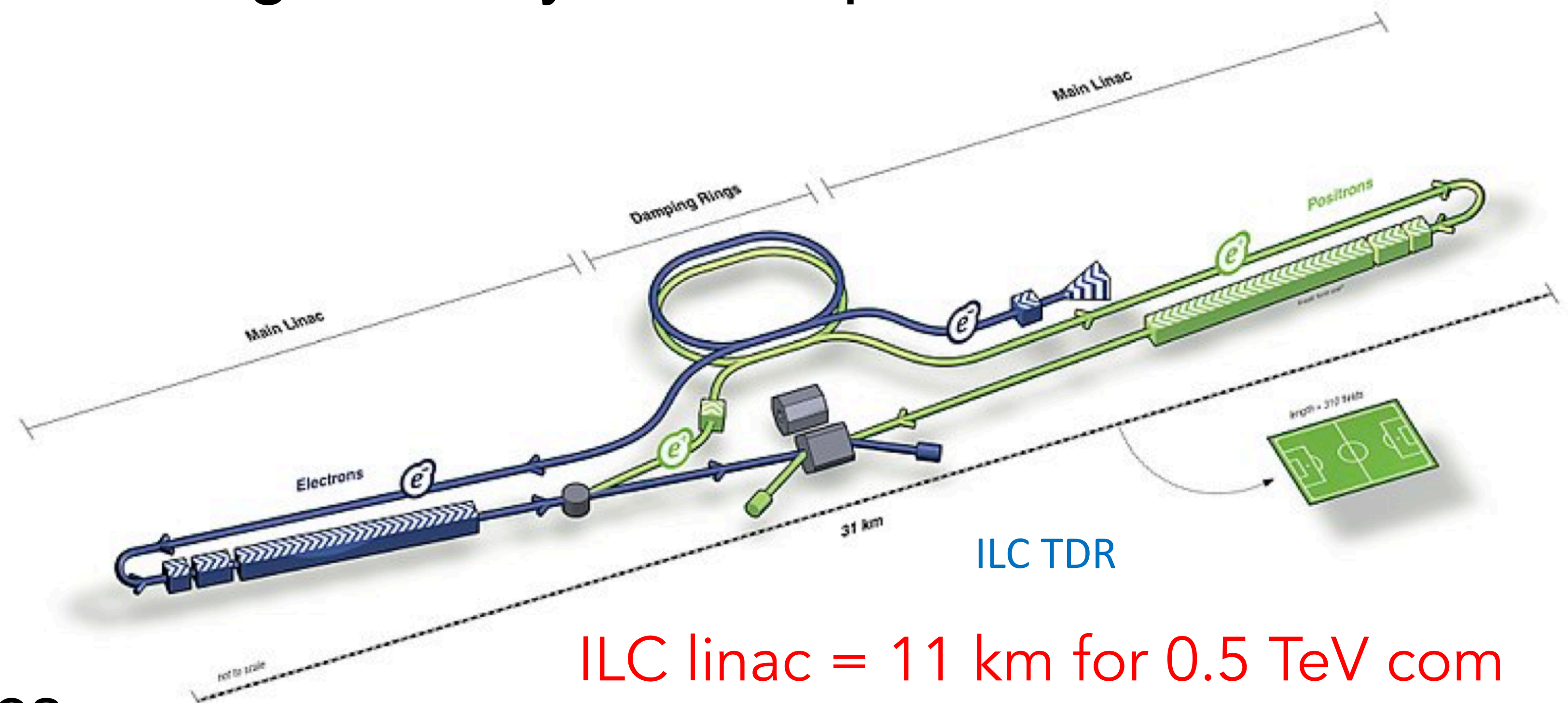
Repurpose an existing (future) conventional RF linear collider facility

- Reuse existing tunnels and infrastructure

Advanced and Novel Accelerators – High fields yield compact linacs

- sub-km linac for TeV
- few km linac for 10 TeV



ILC linac = 11 km for 0.5 TeV com

Example: ILC facility

- Replace RF with plasma stages
- e.g., LWFA at 2.3 GV/m over 11 km yields 50 TeV com

FermiLab site

- Multi-TeV ANA collider possible

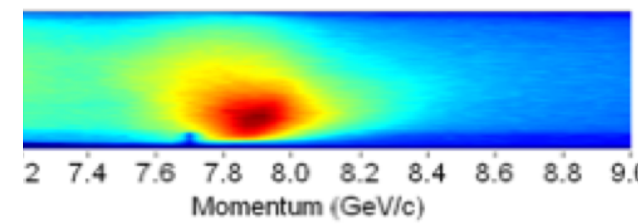
High energies (>10 TeV) accessible in conventional accelerator facility footprint

Rapid Experimental Progress Since Last Snowmass

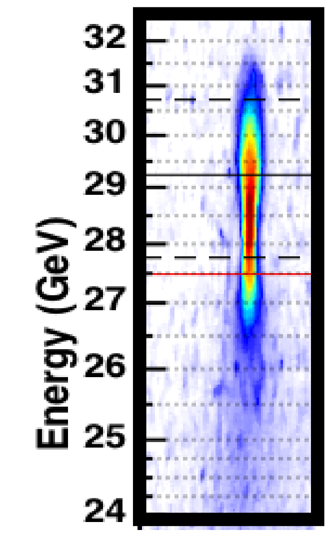
LWFA: 8 GeV **energy gain** in 20 cm stage using BELLA PW laser

PWFA: 9 GeV in 1.3 m using SLAC at FACET

New: 12 GeV from LWFA at U Texas (submitted)

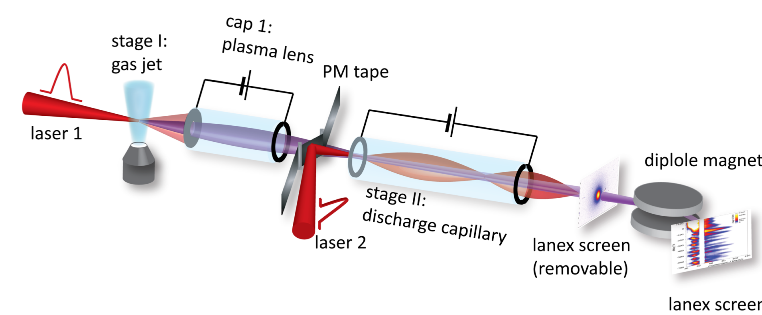


A. J. Gonsalves et al. PRL (2019)



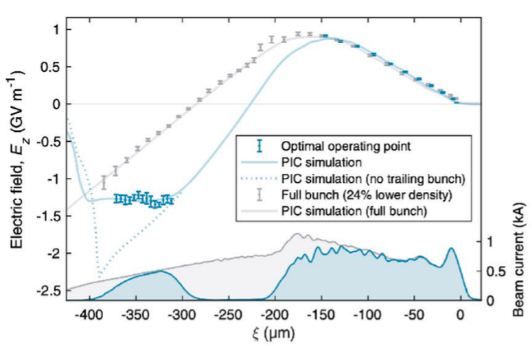
M. Litos et al. PPCF (2015)

Proof-of-principle **staging** of LWFAs (~100 MeV energy gain) using plasma-based stage coupling; multi-GeV soon



S. Steinke et al. Nature (2016)

Optimized beam loading in PWFA enables uniform, **high-efficiency** acceleration

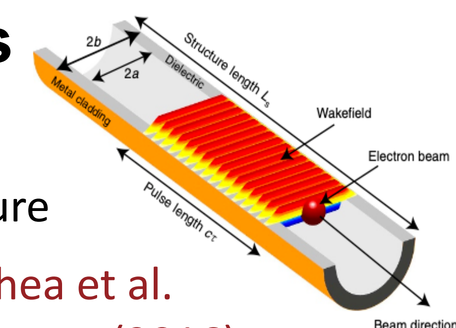


42% transfer efficiency with 0.2% energy spread

C. A. Lindstrom et al. PRL (2021)

Demonstration >1 **GeV/m gradients** SWFA dielectric structures.

GeV/m structure



B. O'Shea et al. Nature Comm. (2016)

Plasma recovery at high rep-rate

R. D'Arcy et al., Nature (2022)

X-ray FEL at 27nm by LWFA (Shanghai 2021) demonstrate **beam quality**

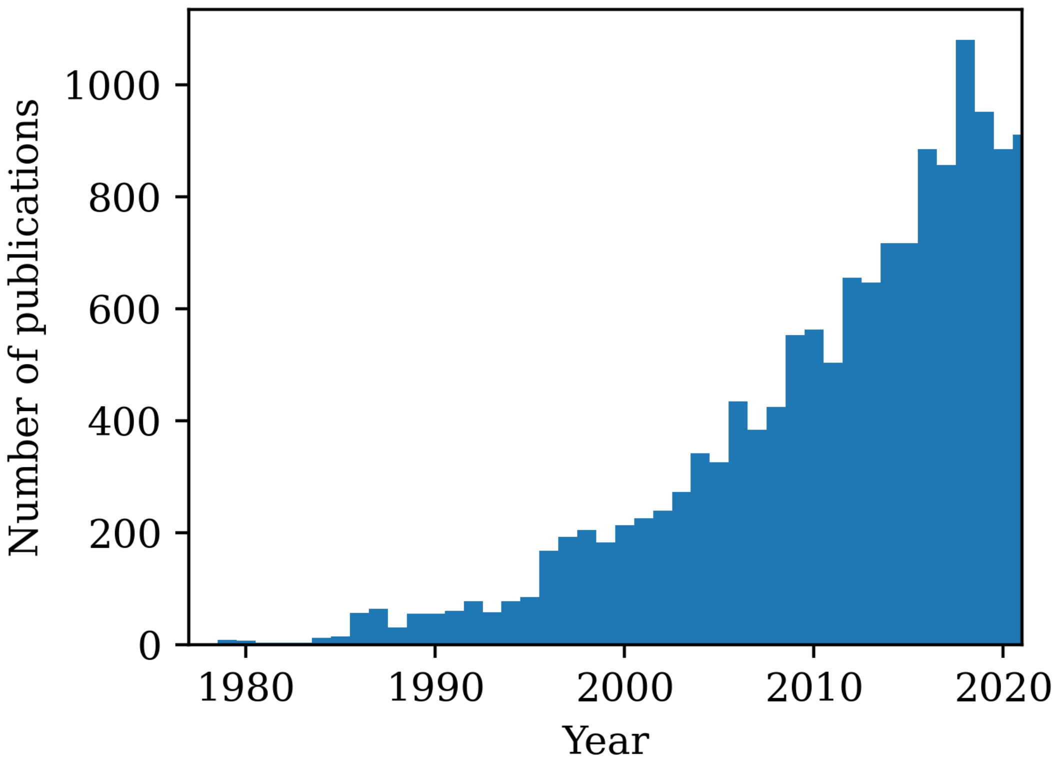
LWFA-FEL: W. Wang et al, Nature Vol 595 (2021)

Drivers: Superconducting XFELs, New laser technology (fibers, Thulium) promise high average power at high efficiency

Also: positron PWFA, hollow channels for low emittance growth, laser-triggered injection for 0.1 micron emittance with path to nm-class…

Worldwide Research on ANA is Vigorous and Rapidly Evolving

- Example: Journal publications on laser-plasma wakefield accelerators
- > 1000 papers/year!
- Intense international competition: potential loss of US leadership



Google Scholar Search Journal publications containing the phases: 'Laser' and 'Plasma' and 'Wakefield' and 'Acceler*'. (citations excluded)

- Laser R&D is also vigorous and rapidly evolving
- 2018 Nobel Prize in physics for chirped pulse amplification lasers (Strickland and Mourou)

AAC R&D Facilities World-wide

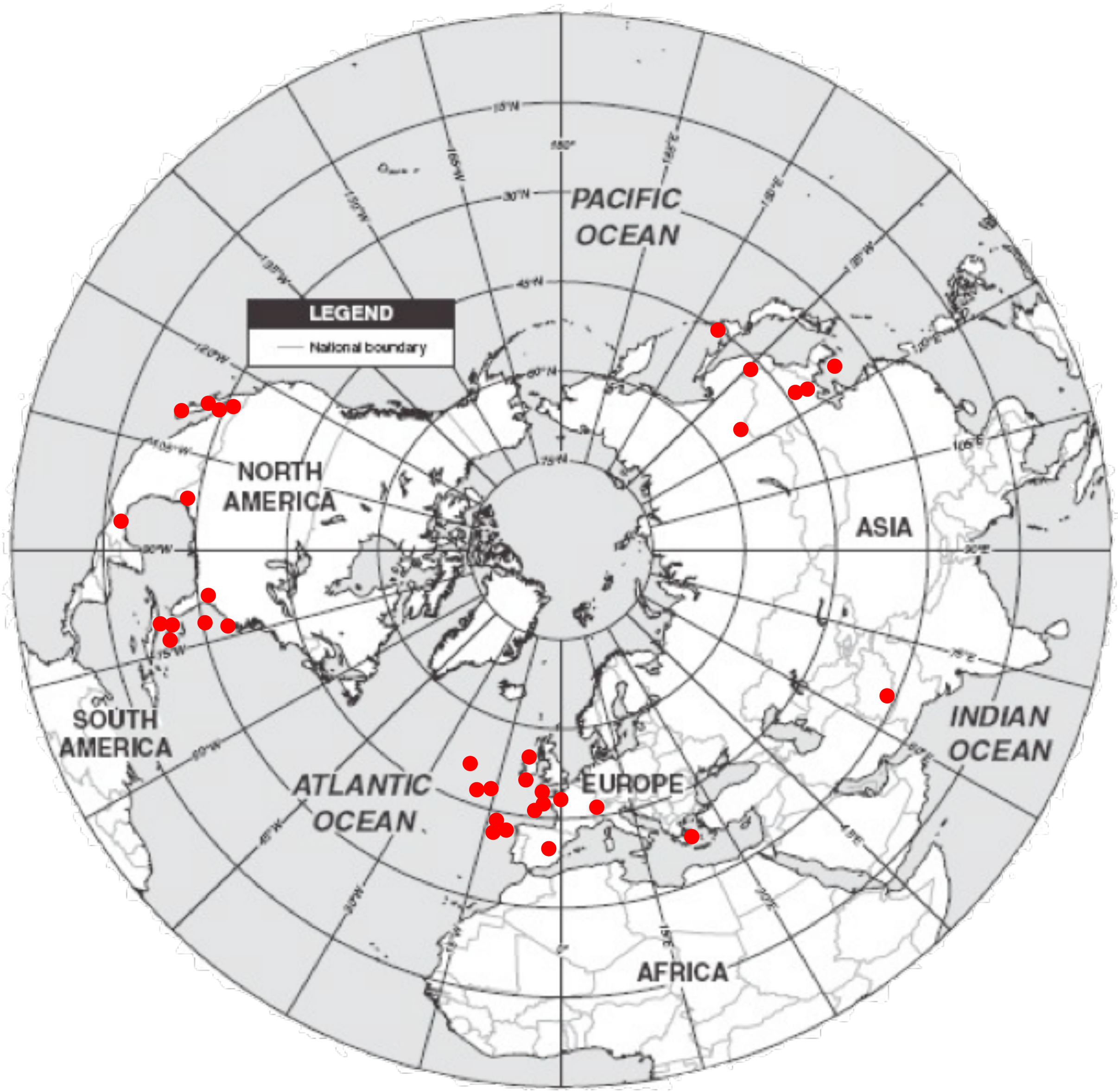
SLAC

US LWFA R&D Laboratories:

- LBNL – BELLA
- LLNL – JLF
- BNL – ATF
- SLAC – MEC
- U. Texas
- U. Michigan
- LLE (Rochester)
- U. Nebraska
- NRL
- UCLA
- U. Maryland

PWFA/SWFA Laboratories:

- ANL – AWA
- BNL – ATF
- DESY – FLASHForward
- INFN – SPARC_Lab
- SLAC – FACET-II
- CERN – AWAKE (proton)



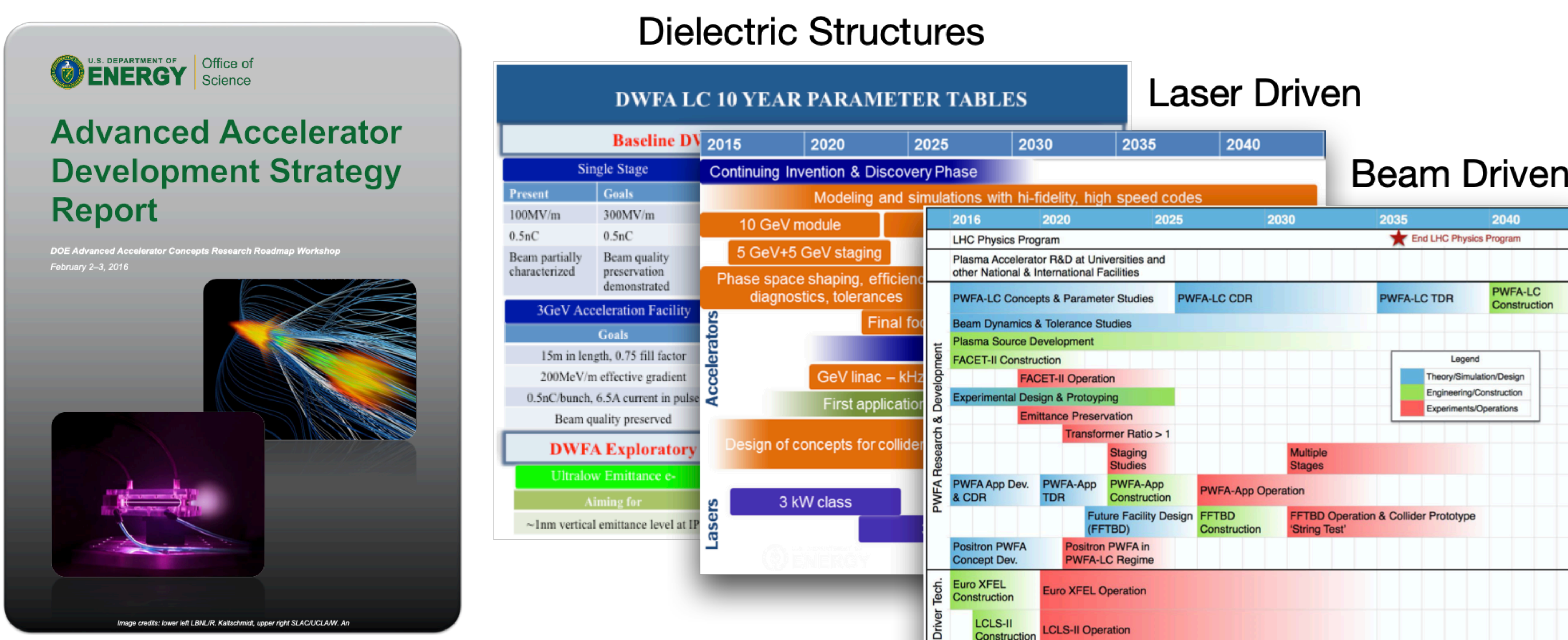
International LWFA R&D Laboratories:

- ELI-Beamlines (Czech)
- ELI-NP (Romania)
- U. Lund (Sweden)
- HZDR (Germany)
- DESY (Germany)
- LMU (Germany)
- Jena (Germany)
- RAL (UK)
- SCAPA (UK)
- U. Oxford (UK)
- LOA (France)
- Apollon (France)
- LULI (France)
- INFN (Italy)
- CoReLS (Korea)
- KPSI (Japan)
- Tsinghua U. (China)
- SIOM (China)
- SJTU (China)
- TIFR (India)
- IAMS (Taiwan)
- ALLS (Canada)
- Weizmann Inst. (Israel)

Compactness of laser systems has led to proliferation of LWFA R&D in laboratories and universities world-wide

Roadmaps for Advanced Technologies

- Roadmaps followed Snowmass 2013 and ensuing HEPAP sub-panel
- Community representatives organized workshops and worked with DOE HEP to define roadmaps for three AAC technologies:
  - LWFA, PWFA and SWFA
- Similar efforts have followed in Europe and US Roadmaps are being revisited as part of Snowmass 2021



Assessment of Limits Indicates Potential for 15 TeV-class

ANA community has accessed potential limits of high-gradient linac technology

- Shaped bunches for high efficiency acceleration without energy spread growth
- Ion motion induced by dense beams can mitigate transverse hosing instability
- Scattering in plasma mitigated by strong plasma focusing
- Positrons can be accelerated in plasma columns
- Energy spread from synchrotron radiation in plasma limited by small beam emittances
- Laser and beam energy recovery may be used for improved efficiency

Additional technical challenges require R&D

- 100's of stages: Beam matching / coupling between including efficiency ≥ 99%
- Small accelerating structures place challenging alignment and jitter tolerances
- Plasma-based beam delivery system and final focus

Wall-plug power will limit energy reach of e+/e- linear colliders based on ANA

- Beamstrahlung limits bunch charge and luminosity requirements increase required power:
- Short beams and low emittance reduce power requirements

$$P_{\text{beam}} \propto \gamma^{5/2}\sigma_z^{1/2}\sigma_x$$

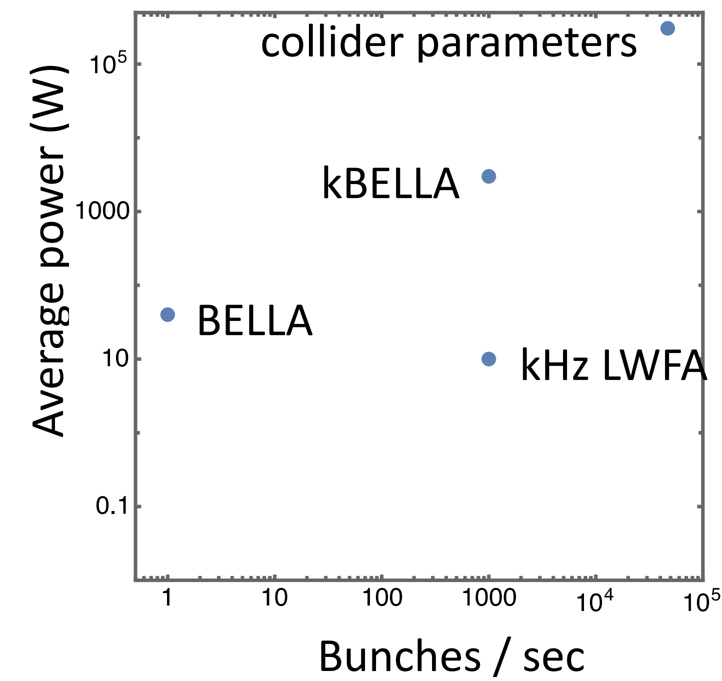
AAC technology is capable of 15-TeV-class e+e- linear collider parameters

Next Steps: ANA Facility Upgrades will Advance Technology and Test Key Remaining Parameters

SLAC

Rapid investment in Europe, Asia, incl. EuPRAXIA ($600M-class)

- US R&D, facility base creates leadership opportunities



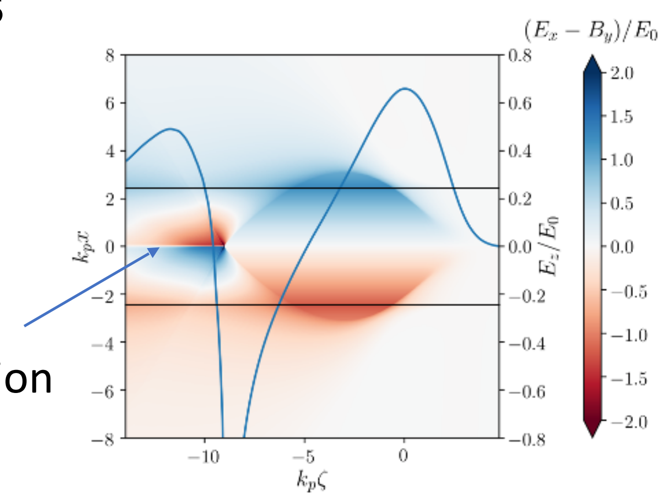
High-average power and high repetition rate plasma accelerators

- Technical challenges: targetry at repetition rate, heat deposition and management (~kW/cm), structure durability
- kBELLA project: kHz, J-class laser. Technology available; precision via active feedback, applications on collider roadmap

Positron acceleration R&D

- Technical challenges: plasma acceleration of stable, high-quality e+ beams, with high efficiency (comparable to e-)
- FACET-II upgrade: plasma-based positron acceleration experiments/tests (e.g., plasma columns or hollow channels)

Wake excited in plasma column



S. Dieterichs et al. PRAB (2019)

Near term applications will establish technology, benefit colliders

- Compton MeV photon sources, FELs, nQED, injectors…
- Societal benefit and increased return on investment for HEP

See – Beam Test Facilities for R&D in Accelerator Science and Technologies arXiv:2203.11290

Near Term: Integrated Design Study

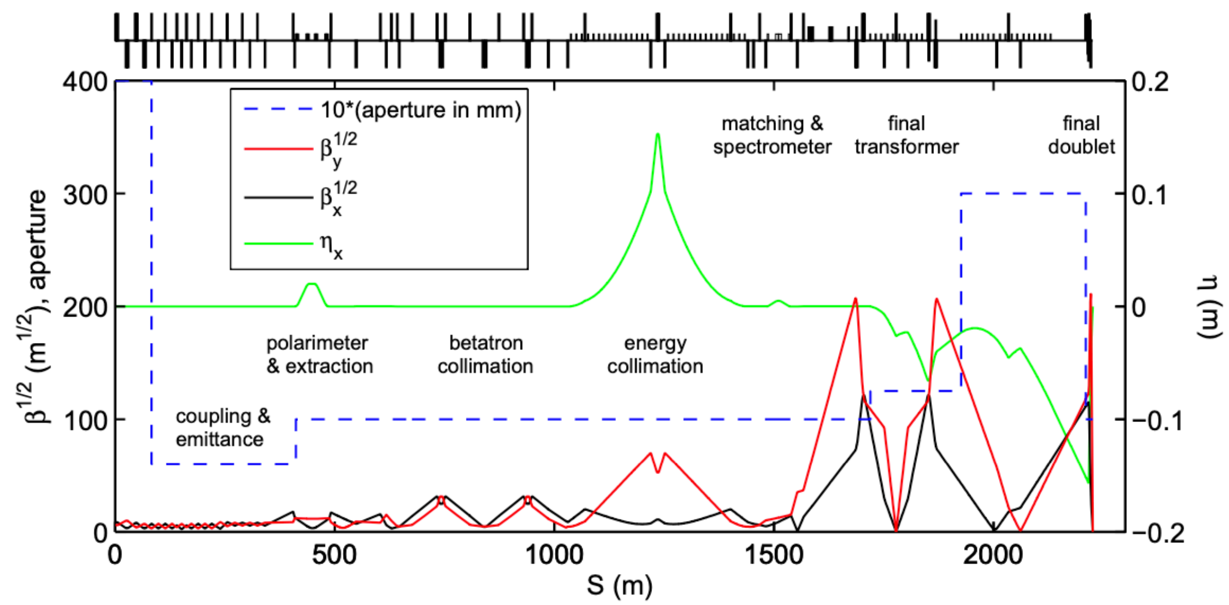
A traditional BDS system contains diagnostic sections and collimation sections in addition to the Final Focus and Machine-Detector Interface.

- Can we develop novel diagnostics (e.g. betatron radiation) to characterize the beam emittance?
- Can we develop novel collimation schemes?

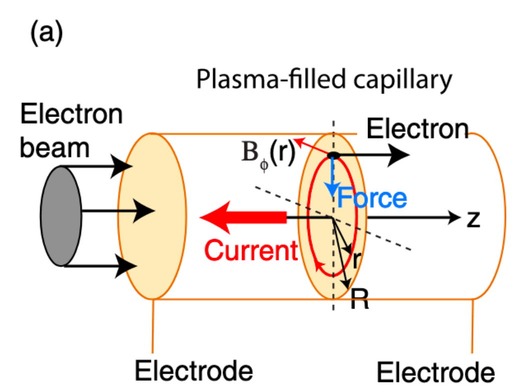
The Final Focus uses the local chromatic correction in the final doublet.

- Can we employ novel chromatic correction techniques with shaped plasma lenses?
- Can we reduce the beam spot using strong focusing from plasma lenses?

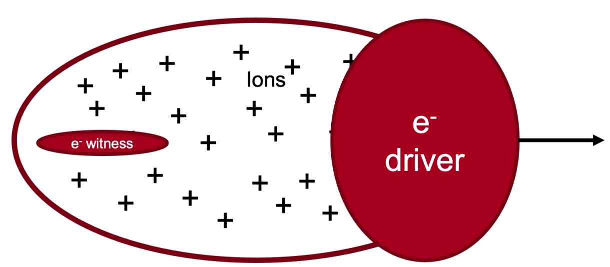
ILC BDS



Active Plasma Lens



Passive Plasma Lens



An integrated design study is needed to understand the challenges and opportunities for all areas of the collider – not just the acceleration

Summary

ANA: potential for multi-TeV collider
- 1-10 GV/m: compact linacs
- Ultrashort bunches: reduce power
- Gamma-gamma, polarized e+e-

Vigorous research, rapid progress
- >1000 pubs/yr

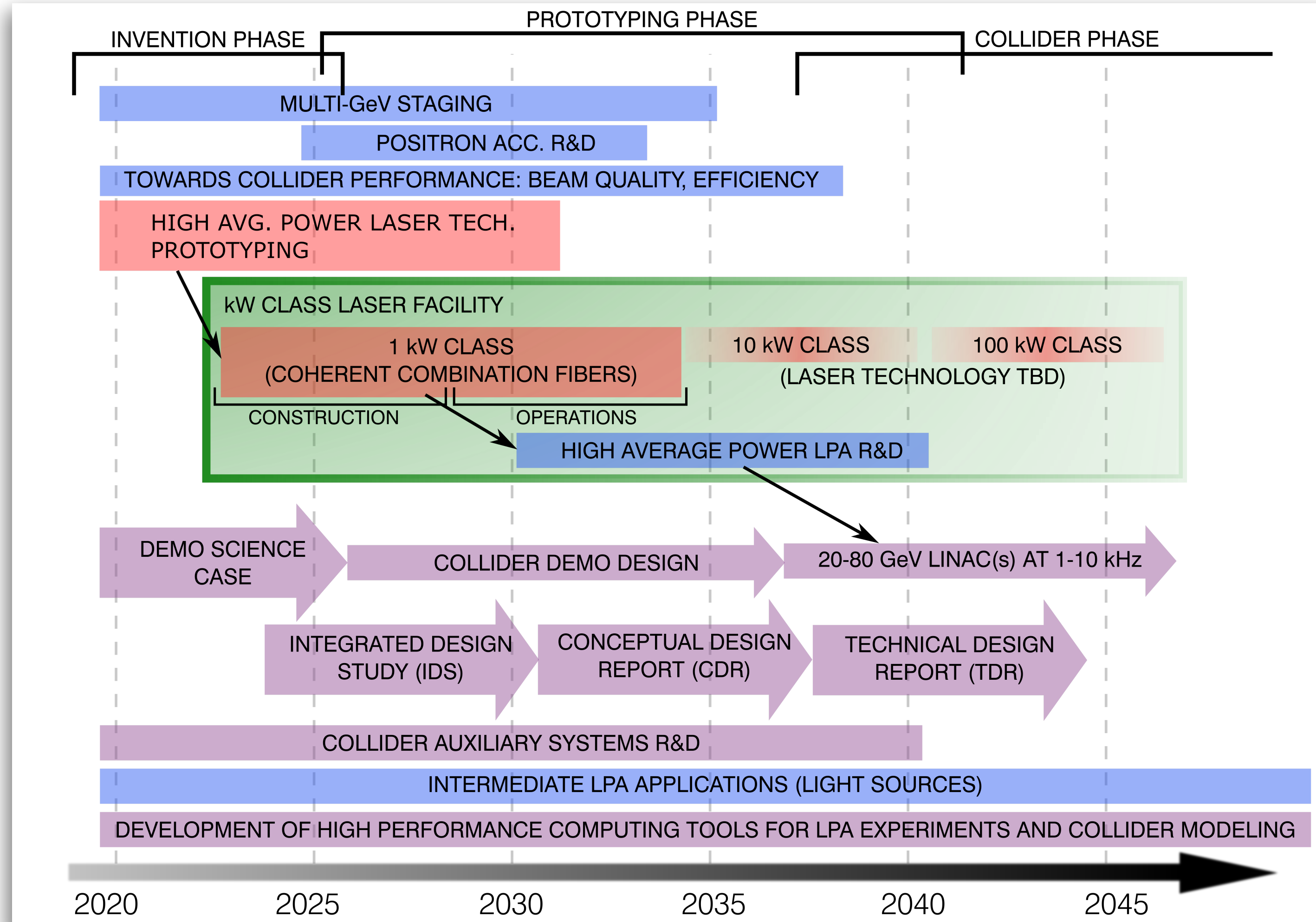
Strong European endorsement
- EuPRAXIA

Next Steps: Upgrade existing facilities
- Remain productive and competitive
- Ensure progress on R&D roadmap

Need for integrated design study
- Include auxiliary systems

Need design for intermediate energy facility
- Build physics case 20-100 GeV

Intermediate applications
- Light sources, compact accelerators



Revision of ANA Roadmaps: in progress

Need input from HEP community to define physics case and guide design of future facilities